

Vortex pattern in a nanoscopic cylinder

Antonio R. de C. Romaguera,^{1,2} Mauro M.Doria,^{1,*} and F. M. Peeters^{2,†}

¹ *Universidade Federal do Rio de Janeiro,*

Caixa Postal:68.528, Rio de Janeiro - RJ, 21941-972,Brazil

²*Universiteit Antwerpen, Groenenborgerlaan 171, B-2020 Antwerpen, Belgium*

(Dated: February 6, 2008)

Abstract

A superconducting nanoscopic cylinder, with radius $R = 4.0\xi$ and height $D = 4.0\xi$ is submitted to an applied field along the cylinder axis . The Ginzburg-Landau theory is solved in three-dimensions using the simulated annealing technique to minimize the free energy functional. We obtain different vortex patterns, some of which are giant vortices and up to twelve vortices are able to fit inside the cylinder.

PACS numbers: 74.20.De,74.25.Ha,74.78.Na,75.75.+a

Keywords: Vortex State, Giant Vortex State, Mesoscopic cylinder

*Electronic address: mmd@if.ufrj.br; URL: <http://www.if.ufrj.br/~mmd>

†Electronic address: francois.peeters@ua.ac.be; URL: <http://www.cmt.ua.ac.be>

Recently, a diode based on vortex physics was proposed[1]. It exhibits new features and opens new prospects for flux line circuit implementations. Potential candidates for resistor, capacitor and inductor based on vortex physics were also considered and they all rely on the choice of sample geometry. Vortex patterns have been previously studied in several geometries with nanoscopic dimensions, such as disks[2],triangles[3] and squares[4]. They were theoretically studied using the Ginzburg-Landau (G-L) theory but only in the two-dimensional limit, where the sample thickness is smaller than ξ . This allowed them to assume that the order parameter is constant along the third direction defined by the field reducing the dimensionality of the problem. The other limit of an infinite long cylinder was studied in [5]. Here we consider the intermediate case of a nanoscopic cylinder with radius $R = 4.0\xi$ and height $D = 4.0\xi$ using the full three-dimensional approach and obtain the vortex states as a function of the applied field perpendicular to its surface.

We minimize numerically the G-L free energy functional using the simulated annealing procedure, discussed in Ref. [6] and in references quoted therein. Every vortex state is characterized by an integer number which is the total vorticity inside the cylinder. In some magnetic field range we find for increasing field and constant vorticity that the vortex evolves from a set of individual vortices with unitary vorticity to another set containing vortices with vorticity larger than one, the so called giant vortex. However for the same conditions of increasing field and constant vorticity the pattern becomes metastable as another vortex state becomes lower in free energy. This change of stability takes place at the matching field[7]. In figure 1 we show the free energy versus the applied field and in figure 2 the corresponding magnetization. The lowest energy curve corresponds to the thermodynamic most stable pattern, the Meissner phase with no vortices, but only up to the first matching field. Above this field the entrance of a single vortex is favored, though it is still possible to keep the system in the Meissner phase but now as a metastable configuration. The small difference in energy around the matching field is able to drive the state to a magnetic hysteresis. In figure 1 we find Multi Vortex States (MVS) and Giant Vortex States (GVS) for fields below a threshold value $H/H_{c2} = 0.96$ and only GVS above it. This result is different from those in Ref [8] where they found only GVS as ground states (MVS appeared as metastable states). The red and blue lines in the magnetization, figure 2, present the full sweep field up and down, respectively. The magnetization curve is truly a collection of several independent lines, each associated to a distinct vorticity which do not cross each

other. As the applied field is swept the vortex pattern jumps from one curve to the next one causing the vorticity to jump with one unit and leading to hysteretic behavior. Figures 2B and 3C show the Cooper pair density of two different states corresponding to the field $H/H_{c2} = 0.785$. The state with $L = 4$ was obtained with increasing the field (red curve) and the state $L = 6$ with decreasing the field. We find twelve independent magnetization lines which implies that a total of twelve vortices fit inside the cylinder. This result is in fair agreement with the eleven vortices found by Baelus et al. [8] for a disk with the same radius, thickness 0.1ξ and $\kappa = 0.28$. Their study is based on a different method, the time evolution of the corresponding two-dimensional system. The maximum number of vortices inside a cylinder follows from the ratio between two areas, the disk surface and the vortex core: $n_s = R^2/\xi^2 = 16$. This value overestimates the true result found here because it does not consider the repulsion among vortices. The first vortex appear at the field $H/H_{c2} \cong 0.21$ and the normal phase is reached at the applied field $H_{c3}/H_{c2} \cong 1.48$. For a disk [8] larger values were found for these critical fields, namely, 0.38 and 1.95 in units of H_{c2} (which is a consequence of the smaller expulsion of the magnetic field in a thin disk).

Acknowledgment A. R. de C. Romaguera and M. M. Doria thank the Brazilian agencies CNPq, FAPERJ and the Instituto do Milênio de Nanotecnologia for financial support. F. M. Peeters acknowledges support from the Flemish Science Foundation (FWO-VI), the Belgian Science Policy (IUAP), the JSPS/ESF-NES program and the ESF-AQDJJ network.

-
- [1] C. C. DE SOUZA SILVA, J. V. DE VONDEL, M. MORELLE, and V. V. MOSHCHALOV, *Nature* **440**, 651 (2006).
 - [2] V. A. SCHWEIGERT and F. M. PEETERS, *Phys. Rev. B* **57**, 13817 (1998).
 - [3] M. MORELLE, J. BEKAERT, and V. V. MOSHCHALOV, *Phys. Rev. B* **70**, 094503 (2004).
 - [4] L. F. CHIBOTARU, A. CEULEMANS, V. BRUYNDONCX, and V. V. MOSHCHALOV, *Nature* **408**, 833 (2000).
 - [5] M. M. DORIA and G. F. ZEBENDE, *Braz. J. Phys.* **32**, 690 (2002).
 - [6] A. R. DE C. ROMAGUERA and M. M. DORIA, *Eur. Phys. J. B* **42**, 446 (2004).
 - [7] E. SARDELLA, M. M. DORIA, and P. R. S. NETTO, *Phys. Rev. B* **60**, 13158 (1999).
 - [8] B. J. BAELUS and F. M. PEETERS, *Phys. Rev. B* **65**, 104515 (2002).

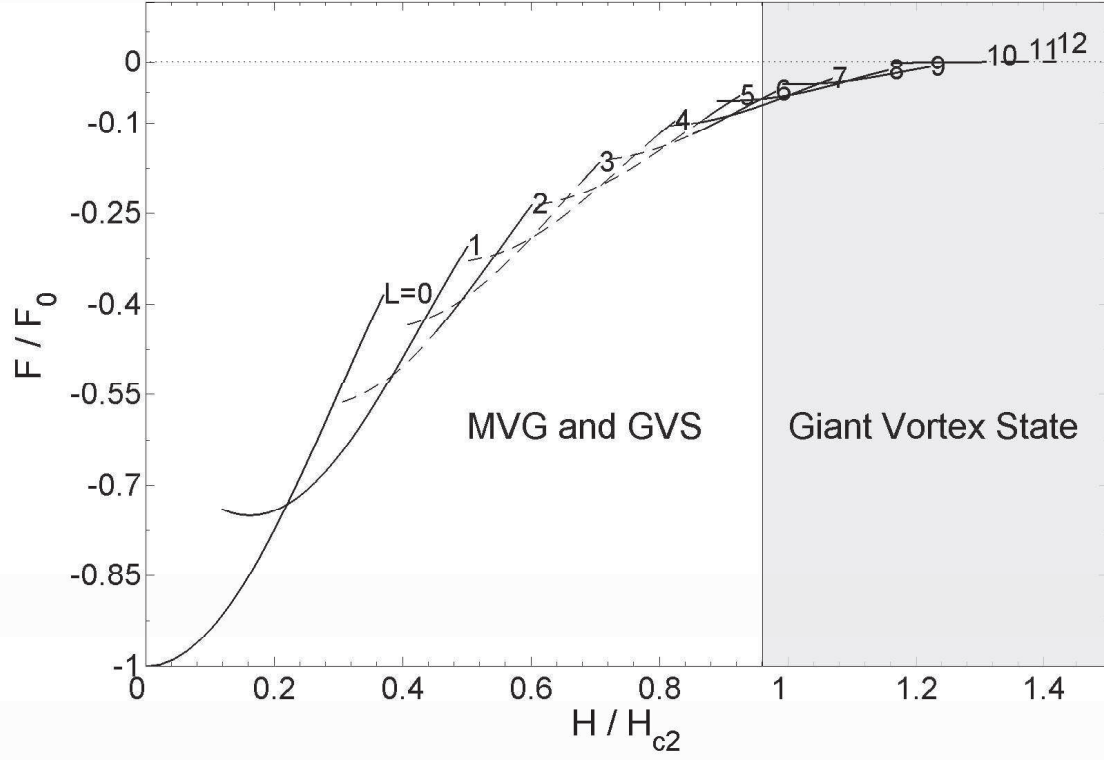


FIG. 1: Free energy of the GVS (solid curves) and the MVS (dashed curves) versus field for a cylinder of radius $R = 4.0\xi$ and thickness $D = 4.0\xi$. The labels inside the curves indicate the vorticity of the system. In the grey region only GVS were observed. In the white region both MVS and GVS were observed.

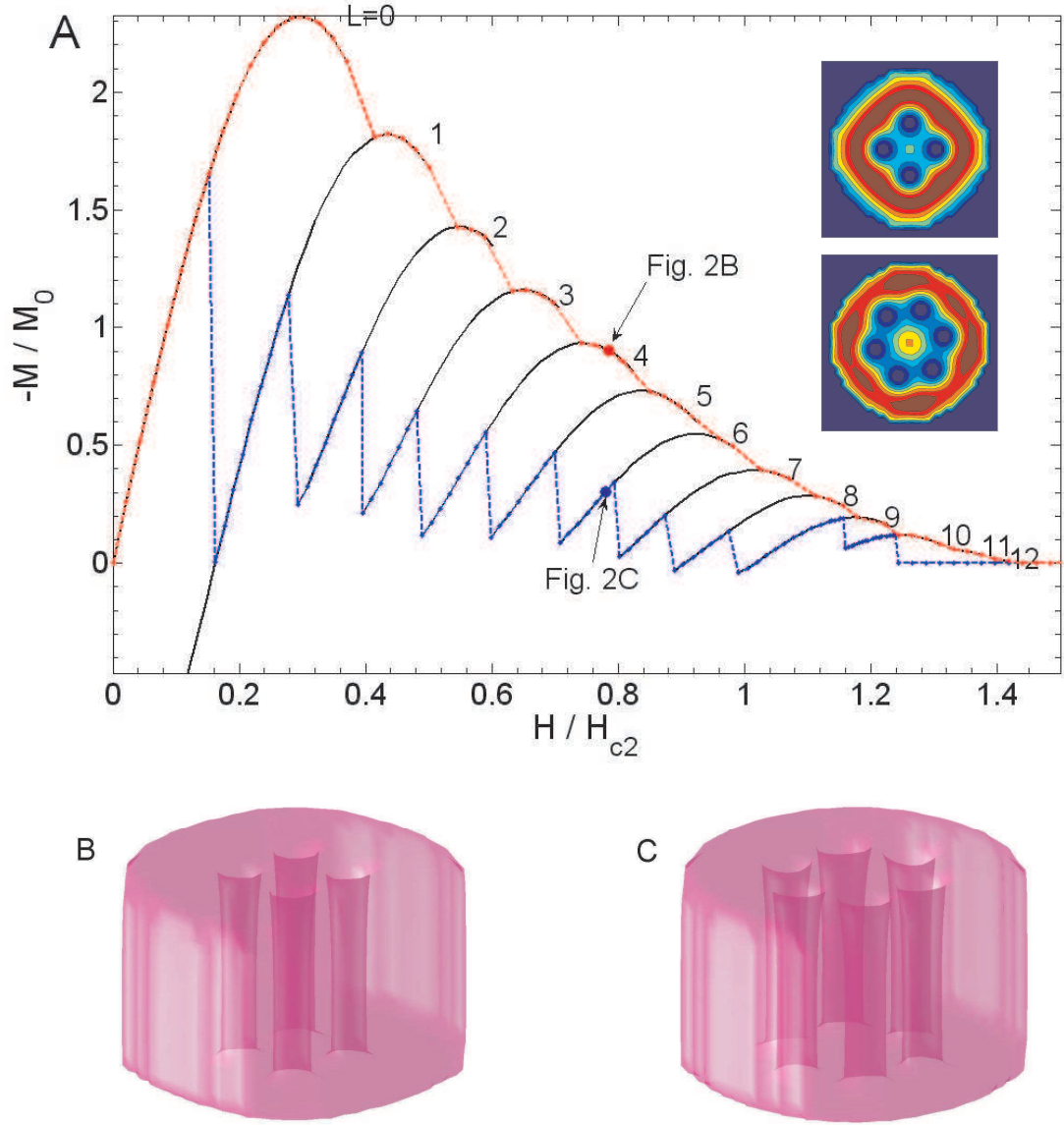


FIG. 2: **(A)** Magnetization versus applied field for the cylinder. The insets are the two dimensional $|\Psi(\vec{r})|^2 = cte$ plots for $H/H_{c2} = 0.785$ with vorticity 4 and 6. **(B)** and **(C)** show the three dimension Cooper pair density isosurface.